# Effects of ENSO on extratropical baroclinic life cycles over the North Pacific

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**Abstract:** El Niño-Southern Oscillation (ENSO) has been shown to influence the seasonal atmospheric circulation over the North Pacific. The present study addresses ENSO modulation of individual extratropical baroclinic life cycles and associated daily weather. Earlier theoretical and observational work established the profound impact of planetary-scale meridional wind shear on the evolution of extratropical cyclones and their upper-level potential vorticity (PV) waves. This concept is utilized to show that the phases of ENSO are characterized by strikingly different time-mean meridional shear, and to provide evidence that El Niño (La Niña) favors cyclonic (anticyclonic) breaking of upper PV waves over the Eastern North Pacific. Examples are taken from the most recent 1997–1999 ENSO.

## 1. Introduction and Background

The North Pacific wintertime atmospheric circulation is known to be sensitive to the state of the tropical Pacific atmosphere-ocean climate system, especially to ENSO. As reviewed by Trenberth et al. (1998), most of the attention regarding the impacts of ENSO on the extratropics has focused on seasonal mean phenomena, such as geopotential height anomalies, shifts in mid-latitude storm tracks, and their impacts on precipitation and surface temperature. The ability to anticipate these effects provides much, if not most, of our present skill in seasonal weather prediction for many parts of the globe (e.g., Barnston and Smith 1996). However, a lesser effort has been directed toward assessing the influence of ENSO on the life cycles of extratropical baroclinic disturbances and their attendant jet streams, fronts, and precipitation; the primary systems responsible for cool-season daily weather. We next review the effects of ENSO on the seasonal extratropical circulation and the influence of planetary-scale flows on baroclinic life cycles.

*ENSO Signatures:* The impacts of ENSO on the atmospheric circulation at higher latitudes over seasonal time scales are reasonably well understood. Anomalies in tropical deep convection associated with ENSO modulate the Hadley circulation, with consequent effects on the strength of the subtropical jet stream (Bjerknes 1969). Modulations of the Hadley circulation are also manifested as anomalies in upper-tropospheric subtropical convergence, which represent a source of Rossby waves that propagate to higher latitudes. The linkages between ENSO and the circulation over the North Pacific and North America are quite strong during winter and can explain the substantial correlations found between ENSO and preferred modes of large-scale extratropical variability, such as the Pacific-North American (PNA) pattern (Horel and Wallace 1981).

One of the most robust of the ENSO signals is the modulation of the intensity and position of the seasonal time-mean upper-level jet stream over the Eastern North Pacific. The associated variation in the time-mean flow occurs north of the region of maximum amplitude in the ENSO tropical precipitation signal. This flow characteristic is illustrated in the composite climatology of the 250-mb wind velocity for the most recent seven El Niño and six La Niña winter seasons (Figs. 1). The salient feature is the strengthening and southward displacement of the jet east of the date line during El Niño (Fig. 1a) and its weakening and northward

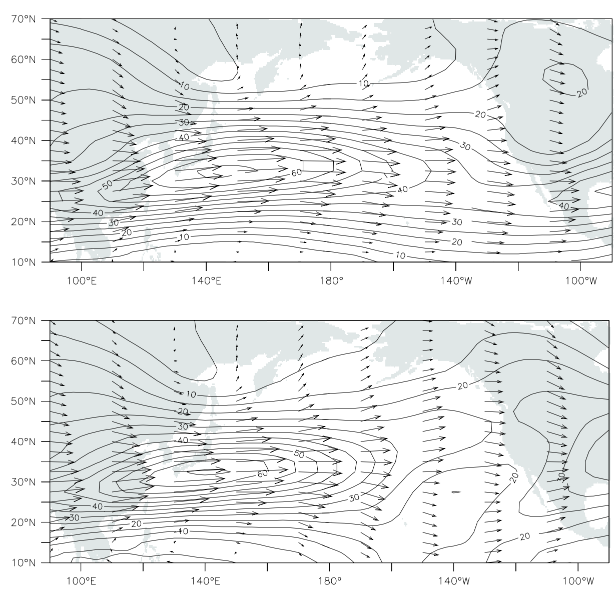

**Figure 1.** January–March time-mean 250-mb wind speed (m s$^{-1}$, lines) and vectors (arrows): (top) El Niño years: 1958, ´66, ´73, ´83, ´87, ´92, ´98; (bottom) La Niña years: 1965, ´71, ´74, ´76, ´89, ´99 (NOAA/Climate Diagnostic Center).

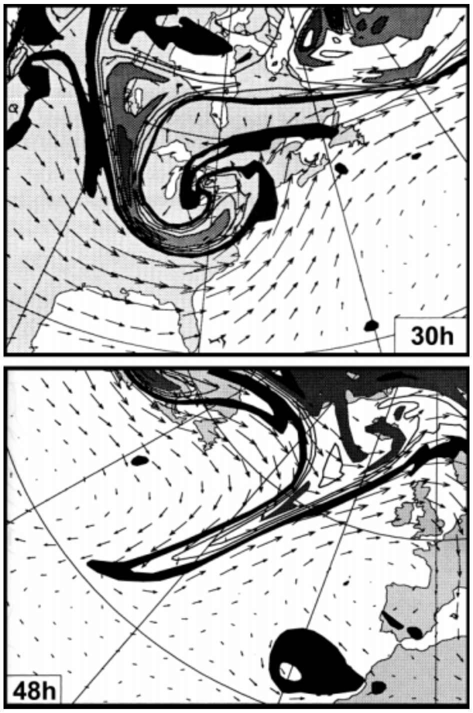


**Figure 2.** Potential vorticity (shaded at 1 PVU intervals, black; 1-2 PVU) and wind vectors: (top) 1800 UTC 26 January 1978 at 310 K; (bottom) 1200 UTC 29 Jan 1994 at 315 K isentropic surface (Simmons 1999).

displacement during La Niña (Fig. 1b). For future reference, we draw attention to the implied variation in time-mean shear within the latitudinal belt (30–50°N) that coincides with the preferred zone for transient synoptic-scale eddies. We will consider the influence of these climatological variations in meridional shear on cyclone life cycles.

*Planetary-scale Influences:* The influence of planetary-scale flows on the life cycles of extratropical cyclones was first illustrated through idealized numerical simulations (e.g., Hoskins 1990; Davies et al. 1991; Thorncroft et al. 1993). These studies demonstrated that the evolution of idealized cyclones (anticyclones) and their associated surface fronts, clouds and precipitation systems, upper-level PV, and eddy fluxes of heat and momentum, is sensitive to a small meridional barotropic wind shear component superimposed upon an otherwise symmetric zonal basic state flow. Cyclones evolving without (within) barotropic shear were referred to as Life Cycle 1, viz., LC1 (Life Cycle 2, viz., LC2). Shapiro et al. (1999) applied this dynamical perspective to observed baroclinic life cycle and determined the environmental shears from cyclone positions relative to the upper-level jet-stream axis. The observed LC1 (LC2) baroclinic developments evolved below the axis (on the cyclonic-shear-side) of the upper jet. Typical examples of the upper-level PV structure associated with the two contrasting life cycles are shown in Fig. 2 (from Simmons 1999). The typical LC2 PV structure (Fig. 2a) is characterized by forward (cyclonic) PV roll up, whereas rearward (anticyclonic) wave breaking and filamentation are evident in the LC1 example (Fig. 2b). As previously shown (Fig. 1), there are dramatic differences in the environmental time-mean upper-level flow and its associated meridional shear over the Eastern Pacific during different phases of ENSO. *Should we therefore expect LC1/LC2 modulation of baroclinic life cycles over the Eastern North Pacific by ENSO?* It is this question that is addressed in this study.

## 2. Time-Mean Flow Structure and Baroclinic Life Cycles during the 1997–1999 ENSO

One of the largest amplitude El Niño events on record occurred during 1997–1998. In response to climate predictions of potentially extreme weather along the western U.S. coastal zone, the National Oceanic and Atmospheric Administration (NOAA), Office of Naval Research, and U.S. Air Force Reserve 53rd Weather Reconnaissance Wing provided emergency support for the North Pacific

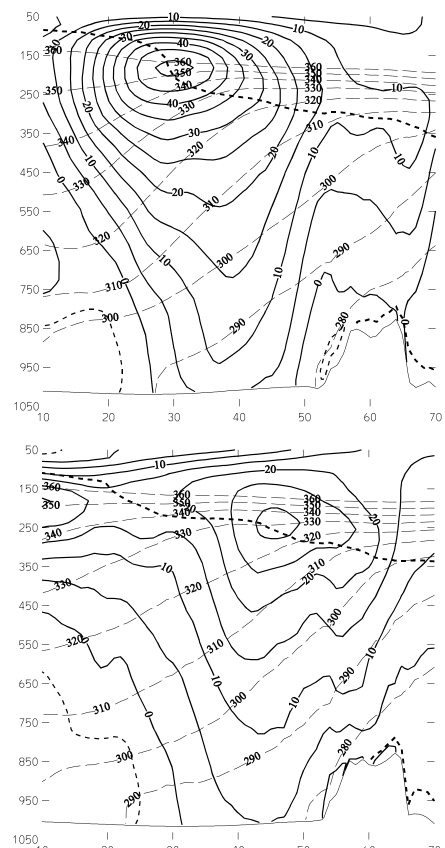


**Figure 3.** January–February time-mean meridional cross sections at 130°W for (top) 1998; (bottom) 1999: zonal wind (5 m $s^{-1}$ intervals, solid lines); potential temperature (10-K intervals between 280–360 K, long dashed lines); 2-PVU tropopause, short-dashed line (ECMWF analyses).

Experiment (NORPEX, Langland et al. 1999) for the deployment of targeted dropwindsondes over the mid-Pacific in order to improve 1–3 day forecasts and warnings. The mid-Pacific targeted dropwindsonde observations were continued during the 1999 La Niña under the NOAA Environmental Modeling Centers Winter Storm Reconnaissance Program. It was the authors participation in these programs that stimulated their investigation of the ENSO modulation of extratropical weather systems.

*Time-Mean Jet-Stream Structure:* We now describe the upper-level jet stream structure for the January–February periods of 1998 and 1999, noting that the time-mean flows for 1998/1999 (not shown) are representative of the longer-term climatology (Fig. 1). Focusing on the Eastern Pacific, Fig. 3 presents the time-mean meridional cross sections of zonal wind, potential temperature and tropopause at 130°W. The key 1998 El Niño features (Fig. 3a) are the ~50 m $s^{-1}$, 200-mb jet core at 30°N and the cyclonic meridional shear zone between 35–55°N that extends from the stratosphere to the ocean. For the 1999 La Niña (Fig. 3b), there is a weaker and more symmetric ~30 m $s^{-1}$, 250-mb jet core at 45°N, with almost no meridional shear in the vicinity of 45°N. The cross sections for these two ENSO phases contain the following differences: 1) opposing latitudinal displacements of the jet over the Eastern Pacific and differing meridional shear in the latitudes of the baroclinic waves; 2) increased middle- to upper-tropospheric baroclinicity in the subtropics during El Niño associated with the response to enhanced deep tropical convection; 3) relatively cooler northern-latitude tropospheric temperatures during La Niña; and 4) a steeper slope of the PV tropopause during El Niño.

*Examples of LC1/LC2 PV Waves:* Representative examples of upper-level PV waves for the ENSO phases are shown in Fig. 4. The El Niño example (Fig. 4a) is a typical forward-breaking PV wave during a LC2 life cycle, as revealed in the color-shaded 320-K PV. In contrast, the La Niña example (Fig. 4b) represents a spectacular LC1 anticyclonic PV wave on both the 320- and 340-K surfaces, including a narrowing filament of stratospheric PV extending into the subtropics. These two examples mirror both the theoretically idealized (e.g., Thorncroft et al. 1993), and observed (e.g., Fig. 2) life cycles. It is recognized that different horizontal tilts of the upper-level PV wave ridge/trough axes (e.g., Figs. 2 and 4) are associated with significantly different meridional momentum fluxes.

*Meridional Eddy Flux Diagnostics:* The occurrence of other examples of preferential LC2 and LC1 horizontal wave tilts during the January–February 1998 and 1999 periods (as in Fig. 4), respectively, led to the hypothesis that ENSO was systematically modulating baroclinic life cycles over the Eastern Pacific. We tested this hypothesis by evaluating time-mean meridional eddy fluxes of upper-level momentum and low-level temperature for January–February 1998 and 1999 (Fig. 5). These fluxes comprise the two principal contributions to the Eliassen-Palm (EP) fluxes. The 1998 El Niño poleward (positive) eddy momentum fluxes at 250 mb (Fig. 5a) are distributed in a narrow (20°) belt along the time-mean jet axis (Fig. 1a), with maximum amplitude at

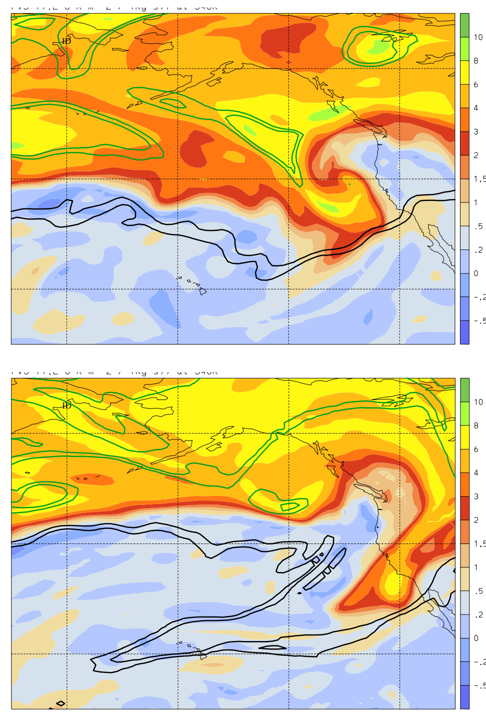

**Figure 4.** Potential vorticity at three isentropic levels for (top) 1200 UTC 6 February 1998 (El Niño); (bottom) 1200 UTC 5 February 1999 (La Niña). 300-K PV (green lines, 2 and 3 PVUs); 320-K PV (color shading, PVU,as in color bar); 340-K PV (black lines, 2 and 3 PVUs) (ECMWF analyses).

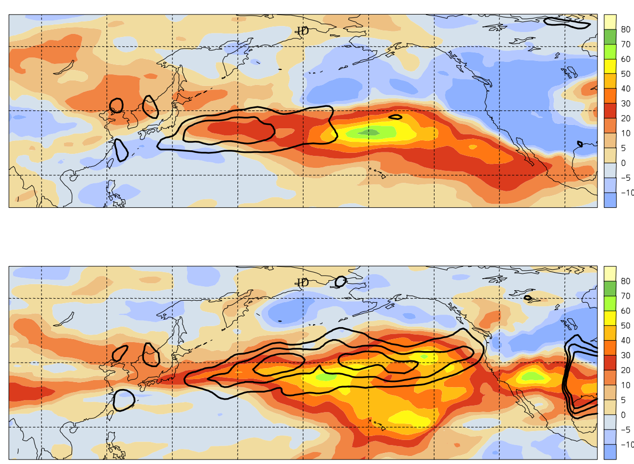

**Figure 5.** January–February time-mean, band-pass filtered meridional eddy fluxes of 250-mb momentum and 925-mb temperature: (top) 1998; (bottom) 1999. Momentum flux ($m^2$ $s^{-2}$, as in color bar). Temperature flux; isolines at 6, 8 and 10 K m $s^{-1}$ (ECMWF analyses).

160°W. In contrast, the 1999 La Niña eddy momentum fluxes (Fig. 5b) bifurcate at 35°N, 170°W; one branch following the northward displaced jet over the Eastern Pacific and the other extending well into subtropical latitudes, in the region of preferred anticyclonic wave breaking (Fig. 4b). This robust signal is consistent with Thorncroft et al. (1993, their Figs. 15b,e) showing enhanced poleward momentum fluxes south of the upper-level jet axis for their LC1 simulation. There are also significant differences in poleward low-level eddy temperature fluxes between the ENSO phases (Fig. 5), the most notable being larger values over the Eastern Pacific for La Niña (Fig. 5b). These larger amplitude temperature fluxes are in the region of enhanced surface anticyclones (not shown) associated with the LC1 upper-level anticyclonic wave breaking. The differences in the EP fluxes between 1998/99 also imply a significantly different mean-flow forcing by the eddies.

## 3. Future Considerations

This short contribution strongly suggests that anomalies in the time-mean environmental flow associated with El Niño and La Niña lead to preferential baroclinic life cycles over the Eastern North Pacific, that closely mimic the idealized LC2 and LC1 paradigms, respectively. It remains for future research to 1) extend the present diagnostics to additional ENSO events, including surface cyclone/frontal structure, 2) assess the influence of LC1/LC2 wave-mean flow interactions on seasonal-mean ENSO circulation anomalies (e.g., Kok and Opsteegh 1985), 3) test the proposed hypothesis through idealized experiments with, e.g., full physics, high-resolution GCMs. 4) assess whether contemporary GCMs used for seasonal and interannual climate predictions are capable of resolving the synoptic-scale characteristics of the LC1/LC2 life cycles, 5) investigate downstream (upstream) energy dispersion (e.g., Wernli et al. 1999) for the contrasting ENSO phases, 6) determine whether ENSO modulates the location and amplitude of sensitive regions within which initial analysis errors strongly impact the 1–10 day predictability of weather events. If the latter effects are significant and systematic, ENSO forecasts should be used in the design of observing systems and strategies for improving numerical weather prediction over the data-sparse Pacific.

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